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Computational analysis of energy separation in a counter-flow vortex tube based on inlet shape and aspect ratio

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ABSTRACT

This article describes the energy separation with the simulation of a three dimensional flow field in Ranque-Hilsch vortex tube. Rectangular and trapezoidal shaped inlets with varying aspect ratio are compared and analyzed while other geometrical parameters are held constant. Air is used as a working fluid. The nature of flow field inside the vortex tube is observed for different cases at an inlet pressure condition of 6 bar (absolute). From the results, it is observed that inlet with higher aspect ratio gives higher temperature separation. The trapezoidal inlet configuration is found to give higher temperature separation as compared to a rectangular shape. The streamlines emanating at the hot and cold end exits for both the rectangular and trapezoidal are visualized. Residence time for two shapes is calculated and found to be higher for trapezoidal shape. The increase in turbulence kinetic energy for the cold end exiting streamlines at the dividing region between core and periphery could be an important factor towards energy separation.

1. Introduction

Ranque-Hilsch vortex tube is a device in which air is fed tangentially inside a tube and exits axially at both the ends of the tube. One outlet emerges as a hot air from the periphery of the tube farther from the inlet (termed as hot end) and the other outlet emerges as a cold air from a centre of the tube near the inlet (termed as cold end). This phenomenon is referred to as temperature separation effect. The extremities of hotness and coldness from the appropriate exits are controlled by the position of the deflecting cone placed at the centre of the tube at the hot end as shown in Fig. 1.

The phenomenon of temperature separation effect was first observed by Ranque in 1931 when he was working in a carpentry shop to remove the dust by a cyclone [1]. Despite the simplicity of its geometry, the energy separation phenomenon is quite intriguing. Various theories have been proposed in the literature to explain the "temperature separation" effect since the initial observations by Ranque [1]. In his pioneering work on the vortex tube, Hilsch [2] suggested that angular velocity gradients in the radial direction give rise to frictional coupling between different layers of the rotating flow resulting in the migration of energy via shear work from the inner layers to the outer layers. Other investigators have attributed the energy separation to work transfer via compression and expansion. Several variations of this theory are described in the literature, differing according to the mechanism that drives the fluid motion. Harnett and Eckert [3] referred turbulent eddies as the cause for temperature separation. Ahlborn and Gordon [4] described an embedded secondary circulation responsible for energy separation. Stephan et al. [5] proposed the formation of Gortler vortices on the inside wall of the vortex tube that drive the fluid motion. Kurosaka [6] ascertained the temperature separation as a result of acoustic streaming effect that transfer energy from the cold core to the hot outer annulus. Gutsol [7] hypothesized the energy separation to be a consequence of the interaction of micro volumes in the vortex tube. Several numerical and experimental studies of the Ranque–Hilsch vortex tubes have been investigated since then and continue even today [8–15].

Promvonge and Eiamsa-ard [16] studied the flow physics extensively in the vortex tube with a snail entrance. This could help to increase the cold air temperature drop and improve the vortex tube efficiency in comparison with the original tangential inlet nozzles. Promvonge and Eiamsa-ard [17] again reported the effects of the number of inlet tangential nozzles, the cold orifice diameter, and tube insulations on the temperature reduction and isentropic efficiency in the vortex tube. Gao et al. [18] used a special pitot tube and thermocouple techniques to measure the pressure, velocity

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Nomenclature

Notation

C	cold end
d	cold end orifice diameter
D	vortex tube diameter
g	acceleration due to gravity
h	height of the inlet nozzle
H	hot end
I	inlet
k	turbulent kinetic energy
L	length of the vortex tube
M	mach number, Molecular weight
P	pressure
Pr	Prandtl number
R	specific gas constant
T	temperature
v	velocity
w	width

Greek symbols

α	cone angle
Δ	change, gradient
ε	turbulence dissipation rate
μ	viscosity
ρ	density
τ	stress tensor
Ω	angular velocity

Suffix

c	cold end
eff	effective
o	stagnation state
op	operating
w	width
h	hot end
i	index variable n
j	index variable
p	constant pressure
ref	reference
t	turbulent

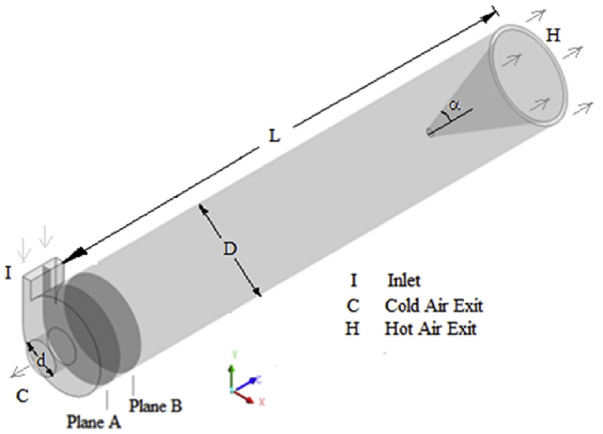

Fig. 1. Geometry of the vortex tube.

and temperature distribution inside the vortex tube which the pitot tube has only a diameter of 1 mm with one hole (0.1 mm diameter). Rounding off the entrance enhanced and extended the secondary circulation gas flow, and improved the performance. Aljuwayhel et al. [19] reported the energy separation and flow phenomena in a counter-flow vortex tube using the commercial CFD code FLUENT and found that the RNG $k-\varepsilon$ model predicted the velocity and temperature variations better than the standard $k-\varepsilon$ model. This is contrary to results of Skye et al. [15] claimed that for vortex tube's performance, the standard $k-\varepsilon$ model performs better than the RNG $k-\varepsilon$ model despite using the same commercial CFD code FLUENT.

Temperature distribution in the tube was provided by the expansion and compression of the compressible working material; thus the compressibility of the working material was essential to the temperature separation in a vortex tube [23,24]. The forced vortex and its effect on the velocity distribution were investigated in other works [12,13]. According to experimental [3,18,28,29] and numerical [13,20–22,25–27] investigations, the pressure at any point in the tube is lower than the inlet pressure, which suggests that expansion happens everywhere in the tube, even at the periphery.

The studies in the counter-flow vortex tube are focused in two aspects i.e. understanding the phenomenon of temperature separation and the next in optimizing the design parameters to achieve lower total temperature at the cold end for cooling applications. The flow field established inside the vortex tube comes from many parameters such as the diameter of vortex tube, diameter of cold end orifice, shape and angle of the hot end conical valve, length of the vortex tube. As the study on inlet parameter is rarely considered in literature, the study of this parameter becomes important towards the temperature separation as the dividing line between the core and periphery is decided mainly by inlet while other parameters are maintained. Across the dividing line, the energy transfer due to work done by viscous stress from the core fluid particles on peripheral fluid particles is referred to as the transfer of turbulent viscous work, while the turbulent viscous work is defined as the work contributed due to shear stress in a turbulent flow field. This comes from the viscous dissipation term in the energy equation. The present work included in this paper describes the flow field of turbulent nature and temperature separation for the rectangular and trapezoidal shapes in the counter-flow vortex tube. The inlet aspect ratio (average width to height of the inlet) is varied for both the shapes and results are analyzed.

2. Methodology

2.1. Experimental study

Experimental studies attempted to investigate the internal flow field in the vortex tube indicate that flow field visualization and instrumentation for temperature and pressure measurement are very difficult. The protrusion of temperature and pressure probes at intervals in the vortex tube alters the original flow field. Smoke flow visualization is found to be futile at inlet pressures higher than 1.5 bar (absolute). Experimental studies are carried out to find the temperatures and pressures at exit and inlet. The diameter of the vortex tube is 0.019 m and orifice diameter at the